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CONTROLLING A NON LINEAR FRICTION MODEL FOR EVOCATIVE SOUND SYNTHESIS APPLICATIONS

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ABSTRACT

In this paper, a flexible strategy to control a synthesis model of sounds produced by non linear friction phenomena is proposed for guidance or musical purposes. It enables to synthesize different types of sounds, such a creaky door, a singing glass or a squeaking wet plate. This approach is based on the action/object paradigm that enables to propose a synthesis strategy using classical linear filtering techniques (source/resonance approach) which provide an efficient implementation. Within this paradigm, a sound can be considered as the result of an action (e.g. impacting, rubbing, ...) on an object (plate, bowl, ...). However, in the case of non linear friction phenomena, simulating the physical coupling between the action and the object with a completely decoupled source/resonance model is a real and relevant challenge. To meet this challenge, we propose to use a synthesis model of the source that is tuned on recorded sounds according to physical and spectral observations. This model enables to synthesize many types of non linear behaviors. A control strategy of the model is then proposed by defining a flexible physically informed mapping between a descriptor, and the non linear synthesis behavior. Finally, potential applications to the remediation of motor diseases are presented. In all sections, video and audio materials are available at the following URL: http://www.lma.cnrs-mrs.fr/~kronland/thoretDAFx2013/

1. INTRODUCTION

Non-linear friction phenomena occure when strongly coupled objects are interacting. It can produce annoying sounds such as brake squeals, door creaks, or vessel squeaks. But such mechanisms are also the basis of bowed string instruments such as violins or cellos, which produce sweet musical sounds. Modeling and synthesizing such acoustical phenomena have therefore been an issue in different contexts, from mechanics and tribology to sound modeling and computer animations. Among these examples, the first ones are for instance related to modeling real physical behaviors of non-linear friction to address issues such as wear and breaking of mechanical pieces, in the automotive industry [1, 2, 3]. The other examples mainly refer to studies within musical acoustics [4], with different applications, aiming for instance at improving bowed instrument making.

In the case of computer animation, the goal is completely different, since friction sounds are to be generated and adapted for visual scenes in movies or video games to replace earlier sound effect techniques. These issues have been tackled in different studies in the last ten years, and it is now possible to generate realistic synthetic friction sounds, even in real-time, with powerful synthesis algorithms [5, 6]. Similarly, different studies focusing on the reproduction of sounds from bowed string instruments for making electronic cellos or violins have been conducted, for instance in Stefania Serafin's work on violin sound synthesis [7]. In her work, synthesis models based on both physical [5] and signal approaches [8] are proposed. In the case of audio-graphic applications, the pioneering work of Gaver and van den Doel, who made significant advances for the real-time modeling of basic interactions such as impacting and rubbing an object should be mentioned. A phenomenological model, based on a source-filter approach was proposed by these authors, which enables real-time synthesis of friction sounds by low-pass filtering a noise [9, 10]. Finally, sound synthesis interaction issues have been well established thanks to these studies and one of the present challenges is the control of such models.

Indeed, on the one hand, the studies mentioned above provide powerful algorithms to accurately reproduce the acoustics of friction phenomena. On the other hand, a lot of physical parameters are involved, as in the friction model proposed by Avanzini et al. [5], meaning that it is hard to manipulate these sounds in order to reproduce a specific mental idea, even if the authors give a phenomenological description of the effects on the synthesized sound. For instance, to make the sound of a wet finger, which produces a squeak on a ceramic vessel, the parameters of the contact condition have to be adjusted according to tribological considerations. These parameters are not at all intuitive for a sound designer who is not familiar with physical variables, like stiffness or dynamic friction coefficients. Moreover, the mapping between dynamic parameters, mainly the velocity and the normal force, is extremely complex due to the non-linear friction behavior and the arrival of sudden transitions between different vibrating states, so-called bifurcations, that are alone subject to a large research field.

The problem of controlling non-linear friction sound synthesis is relevant for several reasons. As already mentioned, these models lack intuitiveness for naive users. Second, and this is the main issue of the present article, the deterministic nature of the models imposed by physical considerations makes it impossible to switch from one state to another according to predefined pressure and velocity specifications. For example, if we want to simulate the sound produced by someone rubbing a wineglass with a wet finger, and to make the sound squeak when the velocity and

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pressure values are below a certain value, and conversely, to make it sing on a harmonic mode when the velocity and pressure exceed these values, it is impossible to adapt the physical models as the deterministic behavior of a model behaving as the one proposed by Avanzini et al.. For a set of parameters, and a couple of velocity and pressure profiles, there is only one possible sound, which acoustical behavior cannot be chosen according to predefined pressure/velocity maps. Ideally one would like to propose a tool for various musical applications converging towards the musical dream of Edgard Varese to control music according to his thoughts.

What is the aim of choosing the vibrating behavior according to velocity and pressure maps a priori? Since squeaking, squealing and more generally, non linear friction sounds perceptually convey the sense of effort, we can expect as mentioned in [5] that audition can replace kinesthetic and proprioceptive information in some applications by evoking the effort with such a clearly audible friction behavior. Concretely, we can imagine applications for learning a specific gesture by real-time synthesizing an appropriate friction sound according to gesture descriptors, such as velocity or pressure, but also according to more complex cost functions linked to the fluidity. For instance, by defining a level of fluidity, a sonification strategy where a squeaking sound is generated when the sound producing gesture is below the defined level, and a sweet violin sound is generated when the gesture reaches a sufficient level of fluidity can be proposed. The underlying assumption is here that the squeaks, due to their intrinsic timbral characteristics (or acoustical morphologies) will implicitly encourage the subject to modify the gesture, and guide the person to be more fluid until he or she reaches the defined level of fluidity, from which a tonal sound of a singing wineglass would be synthesized. It would be a really interesting tool because it also enables to choose different levels of difficulty in a learning task for the rehabilitation of motor deceases for instance. But making such a guidance tool necessitates the generation of separate sounds corresponding to the different acoustical behaviors: squeaking, squealing and self-sustained vibrations.

To reach such a flexible synthesis tool, we will use a general perceptual paradigm to describe the sound produced by continuous interactions such as the friction phenomenon. When we hear the sound of a metal plate falling and hitting the floor, we easily recognize the material – e.g. the metal. If this plate is dragged on a rough floor, it is always possible to recognize the metallic nature of the plate, but it is also possible to recognize the continuous sound-producing action – e.g. rubbing. This example points out a general principle of the auditory perception, namely that sounds can be decomposed in two main contributions: one from the resonating object, reflecting mainly its material and its shape; and another from the type of action, such as impacting or rubbing in the case of the previous examples. In other words, the produced sound can be defined as the consequence of an action on an object. Such descriptions of an auditory event have been highlighted in different psychological studies, which pointed out that our perceptual systems uses information from invariants in the auditory signal to recognize the characteristics of the auditory events. Inspired from the ecological theory of visual perception of Gibson [11], the taxonomy of invariant features of visual flow has been adapted to the auditory perception by McAdams [12] and Gaver [9]. This provides a powerful framework to extract the acoustic information which provides sense to a sound.

Based on the previous paradigm, a synthesis method using a classical exciter-resonator model is proposed in this article. This model provides a lot of flexibility due to the separation between the action – e.g. squeaking or squealing – and the resonating object e.g. material, shape. A general exciter model for the different non-linear friction behaviors is further proposed from physical and spectral considerations. The non-linear behaviors will be synthesized with a general additive source model. Finally, the flexibility of the control of this model, that enables the definition of velocity and pressure maps will be presented. At last, perspectives of this work will be summarized.

2. PERCEPTUAL INVARIANTS FOR SOUND SYNTHESIS

The determination of perceptual invariants related to the evocation of sound sources enables the determination of intuitive control parameters for sound synthesis perspectives. For instance, it has been proved in previous works that the damping behavior characterized the material of an impacted object [13]. In line with this result, a damping law defined by two parameters (i.e., global damping and relative damping parameters) has been proposed to control the perceived material in an impact sound synthesizer [14]. In the case of friction sounds, the perceptual differences between rubbing and scratching interaction sounds [15]. We proposed an intuitive control related to the density of impacts that allowed a continuous transition between rubbing and scratching interaction with higher impact density for rubbing sounds[1].

To synthesize and control sounds in an intuitive way, we based our approach on the *action/object* paradigm previously described. This formulation is well adapted to an implementation with a linear filtering (source/resonance). Modeling and controlling the resonator has been done in the case of impact actions. In this case the modes of the resonator were implemented with a resonant filter bank, which central frequencies correspond to the eigen frequencies of the object [16], see figure 1. The perceptual attributes of the object can be controlled by semantic descriptions of the perceived material and shape. This implementation of the resonator will be used in the following. In the framework of the action/object

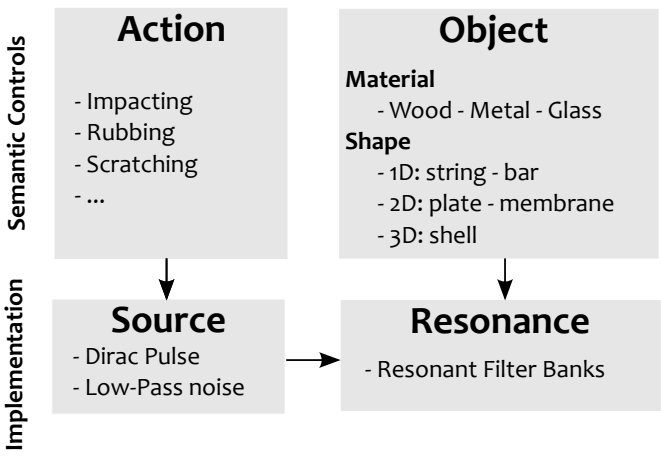

Figure 1: *The Action/Object Paradigm*

[1] A perceptual morphing between scratching and rubbing sounds by manipulating the density of impacts is available here: `http://www.lma.cnrs-mrs.fr/~kronland/RubbingScratching/expe2.html`.

paradigm, the excitation (action) is defined separately from the resonator (object). The associated implementation is a convolution between the excitation signal $e(t)$ and the impulse response $h(t)$ of the vibrating object. Practically, the impulse response $h(t)$ is implemented as a resonant filters bank simulating the modes of the object. However, in the case of non linear friction situations, the main flaw for using of this paradigm might be that the exciter behavior is intrinsically coupled with the resonator from a physical point of view, there are mutual energetic feedbacks between the two interacting objects. Nevertheless, the action/object approach can still be used as long as the excitation signal simulates the acoustic morphologies characteristic of the non linear behavior that is relevant from a perceptual point of view. This excitation model will be presented in the following section, the main issue is sketched on the figure 2.

2.1. Source Modeling

In this section, the modeling of the source related to non linear friction sounds will be examined. For that purpose, physical considerations of such behaviors will firstly be presented. Then, some signal observations made on sound recordings will be considered. At last, a signal model will be proposed according to invariant morphologies revealed by these various approaches.

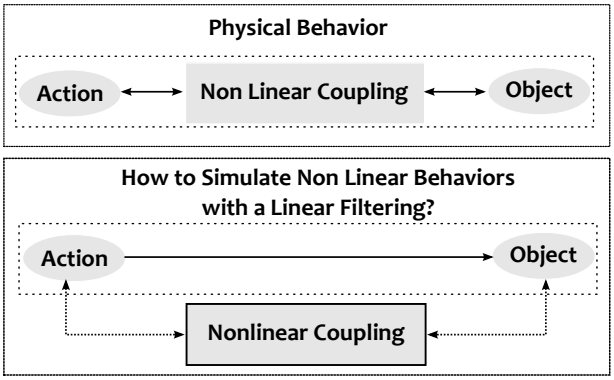

Figure 2: *How to Separate the Non Linear Coupling to Implement Non Linear Behaviors with Linear Filtering*

2.1.1. The Coulomb Friction Model

Non linear friction is a historical topic of physics, that was subject to early researches in the 18th century by Coulomb who gave his name to a specific case of such phenomena. The Coulomb friction can be described in first approximation by a simple phenomenological model – the conveyer belt model – sketched on figure 3. When an object is rubbing another one, and when the contact force between the objects is large enough, the friction behavior can be described by the displacement of a mass held by a spring, and gradually moved from its equilibrium position by a conveyer belt moving at a velocity v, it is called the sticking phase. When the friction force $\mathbf{F_{fr}}$ becomes smaller than the restoring force $\mathbf{F_r}$, the mass slides in the opposite direction until $\mathbf{F_{fr}}$ becomes larger than $\mathbf{F_r}$, it is caused the slipping phase. This model describes the simplest non linear friction behavior, also called stick-slip motion, or the Helmoltz motion. An example is presented in figure 3. If we neglect the slipping phase, the resulting displacement $x(t)$ of

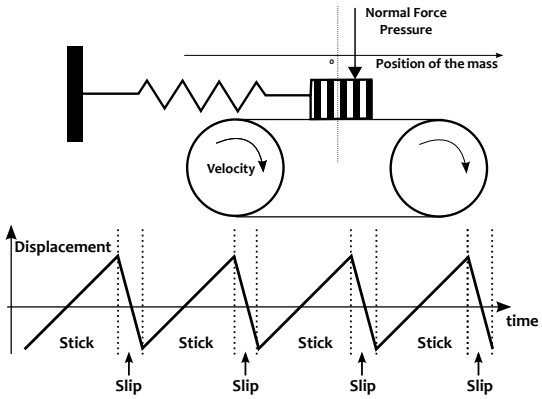

Figure 3: *The Conveyer-Belt Model and a Typical Stick-Slip Motion*

the exciter on the conveyer belt surface corresponds to a sawtooth signal whose Fourrier decomposition is:

$$x(t) = \sum_{k=1} (-1)^k \frac{sin(\omega_0 k t)}{k} \tag{1}$$

This sawtooth behavior can be easily understood: the mass is linearly displaced from its equilibrium position and when it slides back on the belt, it returns to the equilibrium without the slipping phase. The sawtooth is the simplest behavior description that can be given for non linear friction. Several models that take into account a non-zero sliding duration in the return phase can be found. The Fourier decomposition of such a signal is a harmonic spectrum with decreasing amplitude according to harmonic order.

This model provides a first *a priori* about the behavior of the source signal which has to be take into account to simulate the friction phenomenon: the excitation should have an harmonic spectrum. This physical modeling allowed us to determine a signal morphology associated to the non linear friction phenomenon, even if we aware that it cannot be generalized to any friction situation.

2.1.2. Spectral Observations on Recorded Sounds

In this section, some empirical observations of different non linear friction recorded sounds will be presented. Four different situations will be briefly analyzed – a creaky door, a squeaking and singing wet wineglass, and a squeaking wet plate. Except for the door creak, the recordings have been done in an anechoic room with a cardioid Neumann-KM84i microphone positioned about 30 cm above the rubbed object. An analysis of inharmonicity[2] was done for each sound.

- ***Creaky Door.*** The sound presents an harmonic spectrum whose fundamental frequency varies over time. The fundamental frequency does not increase linearly and we assume that it might be related to the rotation speed and the pressure at the rotation axis of the door. The sudden transitions

[2] A partial tracking routine developed by Dan Ellis [17] was used to detect the set of peaks of the spectrum in each frame of the excerpt. A linear regression was applied to the inharmonicity value, $\gamma_n = \frac{f_n}{n f_0} - 1$, where f_n is the n-th peak detected, and f_0 the fundamental. If the spectrum is harmonic the inharmonicity γ_n is 0. The three recordings analyzed provide such results and have a harmonic spectra.

between different vibrating states are noticeable, they are mentioned on the time-frequency plot, but the variation is continuous overall the sound. The large range of variation of the fundamental frequency is also a noticeable characteristic of this signal morphology, it provides a very wide variation in timbre, from a very noisy sound when f_0 is low, to a very harmonic one for higher values. The time-frequency representations of these sounds are presented on figure 4.

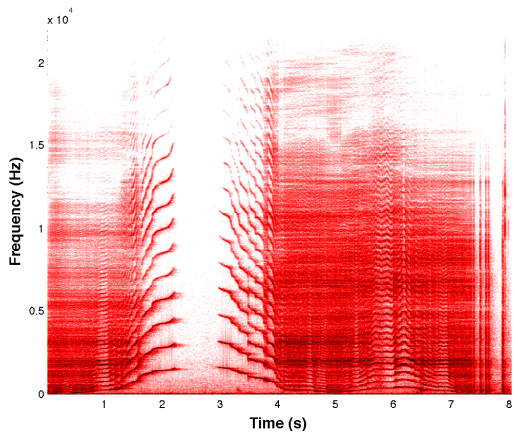

Figure 4: *Creaky Door*

- ***Squeaking Wet Plate.*** This sound is also harmonic but provides less variations of the fundamental frequency than the creaky door. It can be noted that even f_0 does not vary as in the creaky door recording, it varies slowly around a central f_0 value. The modes of the plate are clearly visible and are excited when f_0 is close to them, but the excitation frequency never coincides with them. This observation reinforces the separation between the exciter and the resonator. See figure 5 for the spectrograms of the squeaking and the impulse response of the plate.

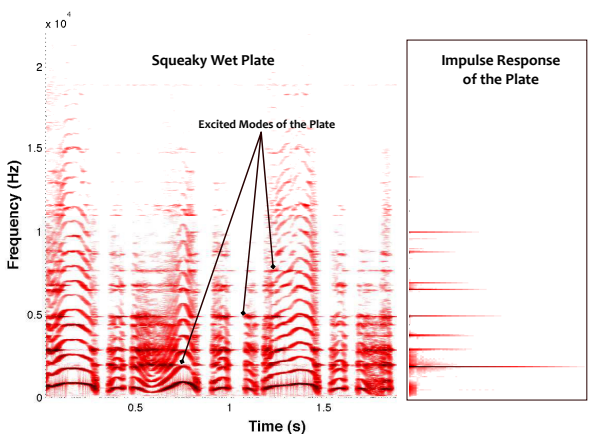

Figure 5: *Squeaky Wet Plate and its Impuse Response*

- ***Squeaking and Singing Glass.*** When a glass is rubbed, the associated sound reveals that several behaviors appear, they are presented on the figure 6. A first one which provides a similar behavior as the squeaking vessel: f_0 varies chaotically around a central value. A second type of behavior (singing) appears when f_0 falls on a mode of the wineglass. The transitions between the squeaking and singing situations seem hardly predictable.

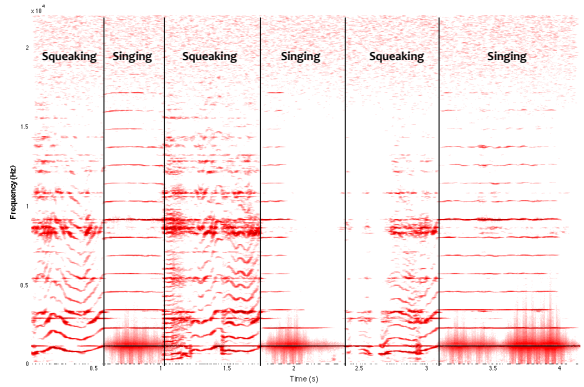

Figure 6: *Squeaking and Singing Glass*

In summary, we hypothesized that the acoustical morphology which characterizes such auditory events is the temporal evolution of the fundamental f_0 frequency of the harmonic spectrum. As it is well known for sustained musical instruments, the different non linear behaviors can indeed be modeled y a harmonic spectrum whose fundamental frequency varies over time. The analyses of the previously recorded sounds confirmed these assumptions.

2.1.3. Signal Model

From the physical considerations and signal observations presented in previous sections, the following general synthesis model of the source $e(t)$ is proposed:

$$e(t) = \sum_{k=1} AM_k(t) sin(\Omega_k(t)) \tag{2}$$

The instantaneous frequency is given by:

$$\frac{d\Omega_k}{dt}(t) = 2\pi k f_0(t) \tag{3}$$

and AM_k the amplitude modulation law for the k-nth harmonic.

- ***Spectral behavior.*** In the material world, we assume that the friction sounds mainly depend on the dynamic pressure $p(t)$ and the relative velocity $v(t)$ between objects. From a signal point of view, the sound morphologies for squeaking, creaky and singing objects, differed by the temporal evolution of $f_0(t)$. Therefore, the following general form for f_0 is proposed:

$$f_0(t) = (1 + \epsilon(t)\gamma)\Phi(v(t), p(t)) \tag{4}$$

Φ represents the fundamental frequency directly defined from the dynamical parameters of the two bodies in contact based on a chosen mapping. Note that for self-sustained oscillations, the fundamental frequency is locked to a mode

of the vibrating object. ϵ is a low pass noise with cutoff frequency defined below 20 Hz. This stochastic part models the chaotic variations of the fundamental frequency that were observed in the case of squeaking or creaking sounds. A low pass noise at a very low cutoff frequency provides oscillations with a period that is sufficiently long to be unpredictable. In the case of self-sustained oscillations, ϵ is null. γ can be defined as a state parameter and equals to 1 for creaking or squeaking situations, and to 0 for self-sustained oscillations. The proposed formulation shows the physical mapping between the couple velocity / pressure and the fundamental frequency, but it has to be noted that the mapping can be done with other descriptors according to the desired applications as it has been mentioned in the introduction.

- ***Amplitude Modulation Behavior.*** In the specific case of the singing wineglass, we observed that low frequency beats appeared in the generated sounds. Rossing found in [18] that the frequency of the Amplitude Modulation is directly linked to, the velocity $v(t)$ of the wet finger which is rubbing the glass rim and, the diameter of the glass D, and defined an explicit expression of $AM_k(t)$ as:

$$AM_k(t) = \frac{1}{k} sin\left(2\pi \int_0^t \frac{v(t)}{\pi D} dt\right) \tag{5}$$

In other words, the smaller the diameter, the higher the velocity and the amplitude modulation, and *vice versa*. Except for the present case of singing wineglass, no other modulation law was found in the literature. As a first approximation, we proposed an Amplitude Modulation law defined by $AM_k = \frac{1}{k}$ available for most cases, based on the physical and signal observations presented in the previous sections.

Finally, in this section we presented in this section a general model that allowed simulating various signal morphologies related to non linear friction phenomena mentioned in introduction. The parameters are summarized in the table 1.

Table 1: *Implementation of the Different Non Linear Behaviors*

	$f_0(t) =$	$AM_k(t) =$
Creaky Door Squeaky Vessel Squeaky Wineglass	$(1+\epsilon(t))\Phi(\Gamma(t))$	$\frac{1}{k}$
Singing Wineglass	$\tilde{f}_{(n,0)}$	$\frac{1}{k} sin\left(2\pi \int_0^t \frac{v(t)}{\pi D} dt\right)$
Bowed String	$\tilde{f}_{(n,0)}$	$\frac{1}{k}$

$\Gamma(t)$ *represents the mapping between the descriptors and the fundamental frequency, the velocity and the pressure in a physical situation –* $\tilde{f}_{(n,0)}$ *is the* n*-th mode of the vibrating object (wineglass or string).*

3. CONTROL

In this section, the control strategy allowing the transitions between the different non linear friction situations will be presented. We aimed at providing a tool which enables a *navigation* across predefined situations with an intuitive interface. For that purpose, the transitions between the different non linear behaviors will be determined from some physical considerations, in particular based on the knowledge on the playability of bowed string instruments. Then a control strategy with descriptors other than the velocity and the pressure will be exposed. At last, an application using the proposed control for the remediation of a handwriting disease will be presented.

3.1. A Physically Informed Mapping

The playability of a bowed string instrument has different definitions depending on whether one takes the acoustic or ergonomics point of view are considered [19]. Here, we based our approach on the acoustic point of view, and we considered the playability as a multidimensional space of physical parameters which characterized the accordance between the played motion and the ideal one, i.e., the Helmoltz motion. Such space has been formalized with Schelleng's diagrams [20] and represents a plot of the degree of playability with respect to the bow force and the bow position. Several studies revealed specific areas where the playability was maximum and areas where the instrument was not playable. They also revealed that the transitions between these areas were very sudden.

Inspired from these Schelleng's diagrams based on physical parameters, we defined the mapping $\Gamma(t)$ between the dynamic descriptors $(v(t), p(t))$ and the fundamental frequency f_0 of the harmonic spectrum. The evolution of f_0 with respect to Γ is freely tunable and for instance, enables the simulation of the bifurcations phenomena. An example of the proposed space is presented in figure 7. This strategy fulfilled the requirements of flexibility we wanted. It indeed leaves the possibility to define a map according to a coherent physical behavior, and beyond these considerations, it also to define behaviors which are theoretically not allowed by physics.

3.2. A Potential Application to Gesture Guiding

The previous section exposed a control strategy of the mapping between dynamic parameters and evoked interaction, this is an interesting tool for sound design or musical application. In this section, the use of this tool for guiding will be briefly presented. The synthetic strategy developed in the previous sections can generate different morphologies whatever control parameters, and possibly independently of the dynamic parameters such as speed and pressure.

Moreover, as was mentioned in the introduction, squeaks evoke particularly the sense of effort, and are more unpleasant. If they are associated in real-time with a gesture, they evoke the clear underlying idea that the gesture is not good and it needs to be changed to become better. Thus, if a descriptor that describes the quality of a gesture, its fluidity for example, is mapped in real-time to different interactions - squeak - self-oscillations - we can create a tool for guiding a gesture by the sound which allows the learning of a specific gesture thanks to a sound feedback.

Such a tool has been proposed to collaborating researchers whose works on the rehabilitation of dysgraphia disease. It is a

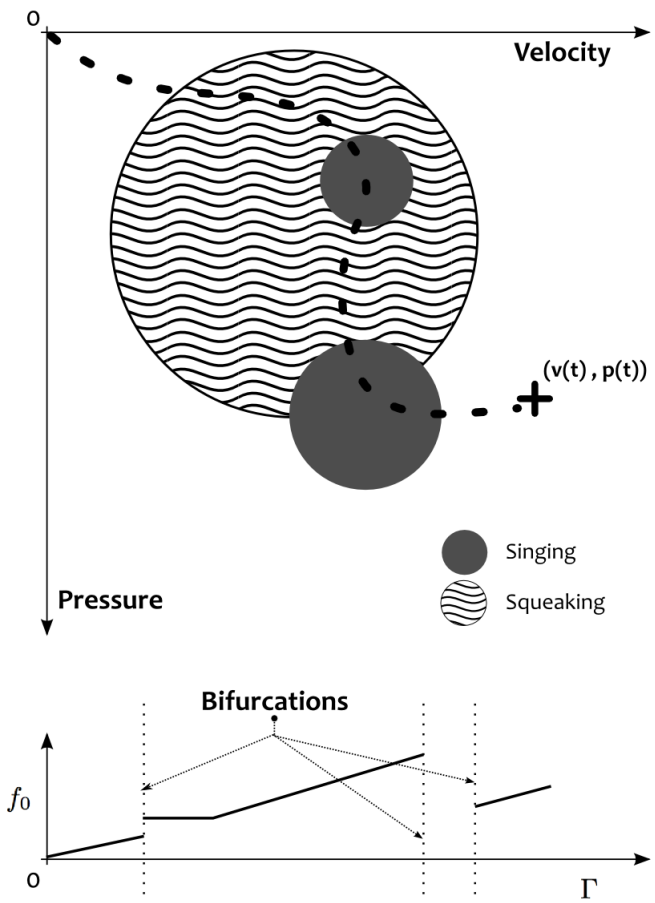

Figure 7: *An Example of Control Strategy by Defining the Vibrating Behavior According to Velocity / Pressure Areas and the Mapping Function Between the Descriptors γ and the Fundamental Frequency f_0*

trouble of handwriting which occurs most often in children and which is characterized by the impossibility for the children to have a fluid gesture. They are able to write a sentence, but it spends very much time and their gesture is very jerky. We proposed a sonifying tool which enables to produce squeaking or self-oscillations according the level of a fluidity descriptor they defined. This tool can be adapted to any descriptor and allows many applications to consider for motor disease remediation of people who have suffered a cardiac or vascular accident and who have motor diseases.

4. CONCLUSIONS

In this paper, we proposed a simple synthesis model based on physical and spectral considerations which enables to simulate separately behaviors such as squeaking, creaking or singing glass. The main goal was to propose a flexible control for musical or guidance applications.

Now, the main issues are to formally evaluate the relevance of such sonification strategy to guide a gesture according to different descriptors. Such a tool has been developed for a rehabilitation protocol of dysgraphia in children and is being evaluated. Perceptual issues about the relevance of the semantic description proposed also has to be done to validate the control strategy.

The calibration for musical purposes is also a big issue and can provide very interesting musical applications.

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